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A Unified Framework for HS-UAV NOMA Networks: Performance Analysis and Location Optimization

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ABSTRACT In this paper, we propose a unified framework for hybrid satellite/unmanned aerial vehicle (HS-UAV) terrestrial non-orthogonal multiple access (NOMA) networks, where satellite aims to communicate with ground users with the aid of a decode-forward (DF) UAV relay by using NOMA protocol. All users are randomly deployed to follow a homogeneous Poisson point process (PPP), which is modeled by the stochastic geometry approach. To reap the benefits of satellite and UAV, the links of both satellite-to-UAV and UAV-to-ground user are assumed to experience Rician fading. More practically, we assume that perfect channel state information (CSI) is infeasible at the receiver, as well as the distance-determined path-loss. To characterize the performance of the proposed framework, we derive analytical approximate closed-form expressions of the outage probability (OP) for the far user and the near user under the condition of imperfect CSI. Also, the system throughput under delay-limited transmission mode is evaluated and discussed. In order to obtain more insights, the asymptotic behavior is explored in the high signal-to-noise ratio (SNR) region and the diversity orders are obtained and discussed. To further improve the system performance, based on the derived approximations, we optimize the location of the UAV to maximize the sum rate by minimizing the average distance between the UAV and users. The simulated numerical results show that: *i*) there are error floors for the far and the near users due to the channel estimation error; *ii*) the outage probability decreases as the Rician factor K increasing, and *iii*) the outage performance and system throughput performance can be further improved considerably by carefully selecting the location of the UAV.

INDEX TERMS Non-orthogonal multiple access (NOMA), unmanned aerial vehicle (UAV), satellite communication, location optimization, Rician fading channels

I. INTRODUCTION

A. BACKGROUND

WITH the developments of mobile internet networks (MIN) and internet-of-things (IoT), there are great challenges for the fifth generation (5G) wireless communication to support massive connectivity and seamless connection under limited spectrum. To solve the above problems, a myriad of physical layer technologies have been proposed, such as massive multiple-input multiple-output (MIMO) [1, 2], non-

orthogonal multiple access (NOMA) [3, 4], millimeter wave (mmWave) [5, 6], small cell networks (SCNs) [7, 8], satellite communication [9, 10] and unmanned aerial vehicles (UAVs) [11, 12]. Among the above technologies, satellite communication and UAV communication are critical segments to support some applications of the upcoming 5G and beyond networks. The satellite communication has become a promising approach due to the growing demand for higher link reliability, greater capability and wider coverage of wireless services.

Unfortunately, owing to the constrained orbital property and latency, some time-critical and locally enhancing sensing applications are very difficult and even infeasible for satellite only. As supplementary, UAV communication has attracted considerable research interests from academic and industry because of its flexibility, higher maneuverability, low-latency and ease of deployment. Therefore, the hybrid satellite/UAV (HS-UAV) communication is important for further applications, such as precision agriculture, disaster response, prehospital emergency care and mineral exploration, among others [13].

On a parallel avenue, non-orthogonal multiple access (NOMA) is another promising technology to improve spectrum efficiency, enhance massive connections and maintain user fairness [14, 15]. Contrary to the conventional orthogonal multiple access (OMA), NOMA can allow all served users to access the same frequency/code resource at the same time, which can be achieved by power multiplexing.¹ In NOMA, all signals are superimposed and sent simultaneously from the transmitter. At the receiver, the individual signal can be obtained by using successive interference cancellation (SIC). Apart from the above benefits, NOMA can also ensure fairness by allocating more power to the far user and few power to the near user. In light of this fact, there are some literature to focus on the contribution of NOMA, see [16–18] and there references therein. Regarding cellular downlink NOMA systems, authors of [16] derived analytical expressions for the outage probability (OP) and ergodic sum rate over Rayleigh fading channels. Exploiting statistical channel state information (CSI), an optimal power allocation strategy was designed by using max-min fairness criterion [17]. In [18], authors investigated the reliability and security performance of the downlink NOMA networks in the presence of in-phase and quadrature-phase imbalance (IQI).

In order to obtain more diversity gain and enlarge the coverage of the network, cooperative communication has been introduced into NOMA to help the communication between the source and the destinations, which has sparked a great deal of research interests, e.g., see [19–24] and the references therein. In [19], Ding *et al.* proposed a new cooperative NOMA scheme, where the near user acts as a decode-and-forward (DF) relay to aid the far user under the assumption of the direct link between the base station and the far user. As an important strategy for 5G, Kim *et al.* extended NOMA into coordinated directly and relay transmission in [20]. Considering the effects of residual hardware impairments on transceivers, Li *et al.* proposed a novel cooperative simultaneous wireless information and power transfer NOMA (SWIPT-NOMA) protocol and derived the analytical expressions for the outage probability and system throughput [21]. In addition, Lee *et al.* in [22] designed a partial relay selection of amplify-and-forward (AF) NOMA networks and investigated the effect of the proposed scheme

on the outage probability and sum rate. Regarding a full-duplex (FD) scenario, Liu *et al.* in [23] derived the analytical closed-form expressions for the outage probability and the ergodic sum rate of cooperative NOMA network, where both perfect and imperfect SIC are taken into account. Do *et al.* in [24] considered the underlay cognitive radio inspired hybrid OMA/NOMA networks, and the outage probability and system throughput of the downlink in the secondary network were investigated and evaluated.

B. MOTIVATIONS AND CONTRIBUTION

Motivated by the aforementioned discussion, in this study, we elaborate on the performance of the HS-UAV networks, where the satellite aims to communicate with NOMA users with the aid of a UAV. To exploit the inherited flexibility of the satellite and UAV communication with respect to better channel conditions ensuring line-of-sights (LoS), Rician fading channel is taken into account. In addition, we consider a more practical case by assuming imperfect CSI at the receiver. More particularly, we derive the analytical approximate expressions for the outage probability and system throughput. To obtain deeper insights, the asymptotic analyses for the outage probability in the high signal-to-noise (SNR) regime and diversity order are performed. Based on the obtained result, an optimal location of the UAV is designed to minimize the average distance between the UAV and users. The main contributions of this work can be summarized as follows:

- We propose a unified framework of HS-UAV NOMA network by using a stochastic geometry approach to model the randomly deployment of ground users. The locations of the ground users follow a homogeneous Poisson point process (PPP) distribution. The probability density functions (PDFs) and the cumulative distribution functions (CDFs) of the user distribution and channel gain between the UAV and the ground users are derived.
- Based on the proposed framework, we derive the approximate analytical closed-form expressions for the outage probability and the system throughput under the delay-limited transmission mode of the random NOMA users in the presence of imperfect CSI. It is shown that there are error floors for the outage probability of the far user and the near user due to channel estimation error.
- We obtain the asymptotic approximate expressions for outage probability of the near user and the far user in the high SNR regime. Furthermore, we obtain and discuss the diversity orders in terms of asymptotic outage probability. It reveals that the derived approximate results remain relatively tight in the moderate and high SNR region.
- To maximize the system performance, we design an optimal location scheme of the UAV by minimizing the average path-loss between the UAV and the ground users. This means that, by carefully designing the location of

¹In general, NOMA can be classified into two categories, such as power-domain NOMA and code-domain NOMA. This paper focuses on power-domain NOMA and we use NOMA instead.

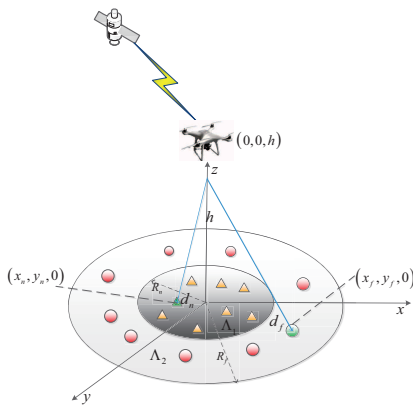


FIGURE 1: system model

the UAV, the outage probability and throughput can be maximized.

C. ORGANIZATION AND NOTATIONS

The rest of this paper is organized as follows. In Section II, system and channel models of the proposed HS-UAV NOMA networks are presented. Section III first derives the analytical approximate expressions for the outage probability and system throughput of the far user and the near user, then discusses the diversity orders in terms of asymptotic outage probability at high SNRs. Section IV presents the optimization scheme of the location of the UAV. Section V provides the numerical simulation results and key findings before we conclude the paper in Section VI.

Notations: In this paper, $|\cdot|$ denotes the absolute value of a scalar, while $\Pr(X)$ represents the probability of a random variable X . In addition, $F(X)$ and $f(X)$ denote the cumulative distribution function (CDF) and the probability density function (PDF), respectively. $\gamma(\cdot, \cdot)$ is an incomplete Gamma function and $X!$ denotes the factorial of X . Finally, $E[\cdot]$ means the expectation operator of random variables.

II. SYSTEM MODEL AND FADING MODEL

A. SYSTEM MODEL

We consider a downlink HS-UAV NOMA network, where one satellite S aims to communicate with terrestrial NOMA users with the aid of a DF UAV relay U , as shown in Fig. 1. The UAV is deployed at a constant height h . It is assumed that the UAV and all users operate in the half-duplex mode, and all nodes are equipped with single antennas. According to the distances between the UAV and the NOMA users, all the served users are classified into two groups Λ_1 and Λ_2 . We assume that the near user D_n in group Λ_1 are located in the circle with radius R_n , and the far user D_f in group Λ_2 are located in ring with inner radius R_n and outer radius R_f ($R_f > R_n$). We also assume that the direct links between the satellite and the users are absent due to the

obstacle or severe large-scale fading. In order to obtain higher performance gain, random user pairing is considered. In the following, we will focus on the performance of the paired user, and other pair performance can be obtained using the same methodology.²

The entire communication is divided into two time slots: 1) Satellite-to-UAV; 2) UAV-to-Users.

1) The first stage: During the first time slot, S sends superposed signal $y_S = \sqrt{a_1 P_S} x_1 + \sqrt{a_2 P_S} x_2$ to U , where P_S is the total power transmitted by S ; x_1 and x_2 are corresponding signals of D_f and D_n , with $E[|x_1|^2] = E[|x_2|^2] = 1$; where a_1 and a_2 denote the power allocation coefficients for D_f and D_n satisfying $a_1 + a_2 = 1$ and $a_1 > a_2$. Thus, the received signal at the relay can be expressed as

$$y_{SR} = h_{SR} \left(\sqrt{a_1 P_S} x_1 + \sqrt{a_2 P_S} x_2 \right) + n_0, \quad (1)$$

where $n_0 \sim CN(0, N_0)$ denotes the additive white Gaussian noise (AWGN).

In practice, it is a great challenge to obtain full knowledge of CSI. The common way is that the receiver estimate the CSI by a training sequence. With this method, the real channel coefficients are affected by the channel estimation error, which can be modeled as $h_i = \hat{h}_i + e_i$, $i = \{SR, RD_n, RD_f\}$, where h_i and \hat{h}_i represent real and estimated channel coefficients, respectively; $e_i \sim CN(0, \sigma_{e_i}^2)$ denotes the channel estimation error which can be approximated as a complex Gaussian random variable [25]. Therefore, the received signals at the relay can be re-expressed as

$$y_{SR} = (\hat{h}_{SR} + e_{SR}) \left(\sqrt{a_1 P_S} x_1 + \sqrt{a_2 P_S} x_2 \right) + n_0. \quad (2)$$

According to NOMA protocol, SIC is applied at U to decode D_f 's signal x_1 first, and then x_2 will be decoded. Therefore, the received signal-to-interference-plus-noise ratios (SINRs) of the signals x_1 and x_2 at U are expressed as

$$\gamma_{x_1}^{SR} = \frac{\rho_{SR} a_1 \gamma}{\rho_{SR} a_2 \gamma + \sigma_{e_{SR}}^2 \gamma + 1}, \quad (3)$$

$$\gamma_{x_2}^{SR} = \frac{\rho_{SR} a_2 \gamma}{\sigma_{e_{SR}}^2 \gamma + 1}, \quad (4)$$

where $\gamma = \frac{P_S}{N_0}$ is the transmit SNR at S and $\rho_{SR} = |\hat{h}_{SR}|^2$ is the channel gain.

2) The second stage: During the second time slot, U decodes and forwards the received signal to the paired users at the same time, and the received signal at D_f and D_n are expressed as

$$y_{RD_f} = (\hat{h}_{RD_f} + e_{RD_f}) \left(\sqrt{b_1 P_R} x_1 + \sqrt{b_2 P_R} x_2 \right) + n_f, \quad (5)$$

$$y_{RD_n} = (\hat{h}_{RD_n} + e_{RD_n}) \left(\sqrt{b_1 P_R} x_1 + \sqrt{b_2 P_R} x_2 \right) + n_n, \quad (6)$$

where P_R is the total transmitted power of U ; b_1 and b_2 are the power allocation coefficients of the relay transmitted to D_f and D_n with $b_1 + b_2 = 1$ and $b_1 > b_2$; $n_f \sim CN(0, N_f)$

²It is noted that some user pairing algorithms are capable of further improving the system performance, which is set aside our ongoing work.

and $n_n \sim CN(0, N_n)$ denote the additive white Gaussian noise (AWGN). The signals x_1 and x_2 are decoded and forwarded to D_f and D_n by U , respectively. Thus, the received SINR at D_f is expressed as

$$\gamma_{x_1}^{RD_f} = \frac{\rho_{RD_f} b_1 \gamma_1}{\rho_{RD_f} b_2 \gamma_1 + \sigma_{e_{RD_f}}^2 \gamma_1 + 1}, \quad (7)$$

where $\gamma_1 = \frac{P_R}{N_f}$ is the transmit SNR to D_f at U and $\rho_{RD_f} = |\hat{h}_{RD_f}|^2$ is the channel gain.

According to the SIC, the SINRs for D_n to decode the desired signal and D_f 's signal are expressed as

$$\gamma_{x_2}^{RD_n} = \frac{\rho_{RD_n} b_2 \gamma_2}{\sigma_{e_{RD_n}}^2 \gamma_1 + 1}, \quad (8)$$

$$\gamma_{x_1}^{RD_n} = \frac{\rho_{RD_n} b_1 \gamma_2}{\rho_{RD_n} b_2 \gamma_1 + \sigma_{e_{RD_n}}^2 \gamma_2 + 1}, \quad (9)$$

where $\rho_{RD_n} = |\hat{h}_{RD_n}|^2$ is the channel gain; $\gamma_2 = \frac{P_R}{N_n}$ is the transmit SNR to D_n at U .

B. FADING MODEL

To ensure the better channel conditions, the LoS links exist between the UAV and the users. In light of this fact, Rician fading is taken into account [26]. In addition, the link between satellite and UAV is assumed to follow Rician distribution.³

The channel coefficient h_j , $j = \{RD_n, RD_f\}$, from UAV to the paired NOMA users D_m , $m = \{n, f\}$, are denoted as

$$h_j = \frac{\hat{h}_j}{\sqrt{1 + d_m^\nu}}, \quad (10)$$

where ν is the path loss exponent and d_m denotes the distance between the UAV and the paired NOMA user D_m ; the coordinates of m -th users D_m and UAV are represented by $(x_m, y_m, 0)$ and $(0, 0, h)$. Thus, the distance d_m can be denoted as

$$d_m = \sqrt{x_m^2 + y_m^2 + h^2}. \quad (11)$$

It is obvious that the distance counts on the location of the UAV and the paired NOMA users. We assume that all users located in Λ_1 and Λ_2 follow a homogeneous PPP. Therefore, the NOMA users are modeled as independently and identically distributed points in Λ_1 and Λ_2 , denoted by ω_m , and PDFs of ω_n and ω_f are given by

$$f_{\omega_n}(\omega_n) = \frac{1}{\pi R_n^2}, \quad (12)$$

and

$$f_{\omega_f}(\omega_f) = \frac{1}{\pi (R_f^2 - R_n^2)}, \quad (13)$$

respectively.

³In fact, Rician shadow has been the prevalent model to capture the characterization of satellite communication systems, our results however can be extended to other fading model.

As discussed above, the link between the satellite and the UAV follows a Rician distribution, and the PDF of the channel gain ρ_i can be expressed as

$$f_{\rho_i}(x) = \frac{(K+1)e^{-K}}{\lambda_i} e^{-\frac{K+1}{\lambda_i}x} I_0 \left(2\sqrt{\frac{K(K+1)x}{\lambda_i}} \right), \quad (14)$$

where λ_i is the mean value of ρ_i ; K is the Rician factor, which is defined as the ratio of the power of the LoS component to the scattered components and $I_0(\cdot)$ denotes the zeroth order modified Bessel function of the first kind [27]. The corresponding CDF is given by

$$F_{\rho_i}(x) = 1 - \mathcal{Q} \left(\sqrt{2K}, \sqrt{\frac{2(K+1)x}{\lambda_i}} \right), \quad (15)$$

where $\mathcal{Q}(a, b) \triangleq \int_b^\infty x e^{-\frac{a^2+x^2}{2}} I_0(ax) dx$ is the Marcum Q-function of first order [28].

Unfortunately, it is difficult, if not impossible, to obtain the exact performance of the considered network. To solve this issue, we use the equality $I_0(x) = \sum_{l=0}^\infty \frac{x^l}{2^{2l} (l!)^2}$ [29], hence the PDF of the channel gain ρ_i can be re-expressed as

$$f_{\rho_i}(x) = \frac{(K+1)e^{-K}}{\lambda_i} \sum_{l=0}^\infty \frac{x^l}{(l!)^2} \left(\frac{K(K+1)}{\lambda_i} \right)^l e^{-\frac{K+1}{\lambda_i}x}. \quad (16)$$

Based on the above formulas, we can get the CDF of the channel gain ρ_i as

$$F_{\rho_i}(x) = 1 - e^{-K} \sum_{l=0}^\infty \sum_{m=0}^l \frac{K^l}{l!m!} \left(\frac{K+1}{\lambda_i} \right)^m x^m e^{-\frac{K+1}{\lambda_i}x}. \quad (17)$$

To evaluate the performance of the user modelled by a PPP, we first obtain the closed-form expressions of the CDF for $|h_n|^2$ and $|h_f|^2$, which are provided in the following proposition.

Proposition 1. Suppose all users follow a homogeneous PPP, using stochastic geometry, the CDF of the squared channel gain $|h_n|^2$ and $|h_f|^2$ are given by

$$F_{|h_n|^2}(x) = 1 - \frac{2}{R_n^2} e^{-\frac{(K+1)x}{\lambda_i}} - K \sum_{l=0}^\infty \sum_{m=0}^l \frac{K^l}{l!m!} \left(\frac{K+1}{\lambda_i} \right)^m x^m \times \sum_{t=0}^m \binom{m}{t} \nu^{-1} \left(\frac{(K+1)x}{\lambda_i} \right)^{-\frac{\nu t + 2}{\nu}} \gamma \left(\frac{\nu t + 2}{\nu}, \frac{(K+1)x}{\lambda_i} R_n^\nu \right), \quad (18)$$

and (19), shown at the top of the next page.

Proof. Based on (12) and (17), for an arbitrary choice of ν , the CDF of $|h_n|^2$ is given by (20), shown at the top of the next page.

After some manipulations, (18) can be obtained.

Similarly, for an arbitrary choice of ν , the CDF of $|h_f|^2$ can be expressed as in (21), shown at the top of the next page.

After some manipulations, (19) can be proved. \square

$$F_{|h_f|^2}(x) = 1 - \sum_{l=0}^{\infty} \sum_{m=0}^l \sum_{t=0}^m \binom{m}{t} \frac{K^l}{l!m!} \times \left(\frac{K+1}{\lambda_i} \right)^m \frac{2x^m}{R_f^2 - R_n^2} e^{-\frac{K+1}{\lambda_i}x - K} \times \nu^{-1} \left(\frac{(K+1)x}{\lambda_i} \right)^{-\frac{\nu t+2}{\nu}} \left(\gamma \left(\frac{\nu t+2}{\nu}, \frac{(K+1)x}{\lambda_i} R_f^\nu \right) - \gamma \left(\frac{\nu t+2}{\nu}, \frac{(K+1)x}{\lambda_i} R_n^\nu \right) \right) \quad (19)$$

$$F_{|h_n|^2}(x) = \int_{I_n} \left(1 - e^{-K} \sum_{l=0}^{\infty} \sum_{m=0}^l \frac{K^l}{l!m!} \left(\frac{K+1}{\lambda_i} \right)^m x^m (1+d^\nu)^m e^{-\frac{K+1}{\lambda_i}x(1+d^\nu)} \right) f_{\omega_n}(\omega_n) d\omega_n \\ = \frac{2}{R_n^2} \int_0^{R_n} r dr - \frac{2}{R_n^2} \int_0^{R_n} e^{-K} \sum_{l=0}^{\infty} \sum_{m=0}^l \frac{K^l}{l!m!} \left(\frac{K+1}{\lambda_i} \right)^m x^m (1+r^\nu)^m e^{-\frac{K+1}{\lambda_i}x(1+r^\nu)} r dr \quad (20)$$

$$F_{|h_f|^2}(x) = \int_{I_f} \left(1 - e^{-K} \sum_{l=0}^{\infty} \sum_{m=0}^l \frac{K^l}{l!m!} \left(\frac{K+1}{\lambda_i} \right)^m x^m (1+d^\nu)^m e^{-\frac{K+1}{\lambda_i}x(1+d^\nu)} \right) f_{\omega_f}(\omega_f) d\omega_f \\ = \frac{2}{R_f^2 - R_n^2} \int_{R_n}^{R_f} \left(1 - e^{-K} \sum_{l=0}^{\infty} \sum_{m=0}^l \frac{K^l}{l!m!} \left(\frac{K+1}{\lambda_i} \right)^m x^m (1+r^\nu)^m e^{-\frac{K+1}{\lambda_i}x(1+r^\nu)} \right) r dr \quad (21)$$

III. OUTAGE PROBABILITY ANALYSIS

In this section, we carry out the outage performance analysis for the paired NOMA users, D_f and D_n . In order to obtain deeper insights, the asymptotic analysis and diversity order are calculated and analyzed.

A. OUTAGE PROBABILITY

For the far user D_f , the outage event will occur in the following three cases: 1) The relay cannot successfully decode x_1 ; 2) The relay cannot successfully decode x_2 ; 3) The relay can successfully decode x_1 and x_2 while D_f cannot successfully decode its signal. Therefore, the OP of the far user D_f can be expressed as

$$P_{out}^{D_f} = \Pr \left(\min \left(\frac{\gamma_{x_1}^{SR}}{\gamma_{th,f}}, \frac{\gamma_{x_2}^{SR}}{\gamma_{th,n}}, \frac{\gamma_{x_1}^{RD_f}}{\gamma_{th,f}} \right) < 1 \right), \quad (22)$$

where $\gamma_{th,f}$ and $\gamma_{th,n}$ are the outage thresholds at D_f and D_n , respectively. In the following theorem, the approximate expression for OP of D_f will be presented.

Theorem 1. *The approximate closed-form expression for the OP of D_f can be expressed as (23), shown at the top of the next page.*

$$\text{where } \zeta_1 = \frac{\sigma_{eSR}^2 \gamma_{th,f} + \gamma_{th,f}}{a_1 \gamma - a_2 \gamma_{th,f}}, \zeta_2 = \frac{\sigma_{eSR}^2 \gamma_{th,n} + \gamma_{th,n}}{a_2 \gamma}, \zeta = \max(\zeta_1, \zeta_2) \text{ and } \psi = \frac{\sigma_{eRD_f}^2 \gamma_{th,f} + \gamma_{th,f}}{b_1 \gamma_1 - b_2 \gamma_1 \gamma_{th,f}}.$$

Proof. See Appendix A. \square

For the near user D_n , the outage events will not occur until both the relay and the near user D_n decode x_1 and x_2 successfully. Thus, the approximate OP of D_n will be

expressed as

$$P_{out}^{D_n} = \Pr \left(\min \left(\frac{\gamma_{x_1}^{SR}}{\gamma_{th,f}}, \frac{\gamma_{x_2}^{SR}}{\gamma_{th,n}} \right) < 1 \right) \\ + \Pr \left(\min \left(\frac{\gamma_{x_1}^{SR}}{\gamma_{th,f}}, \frac{\gamma_{x_2}^{SR}}{\gamma_{th,n}} \right) \geq 1, \min \left(\frac{\gamma_{x_1}^{RD_n}}{\gamma_{th,f}}, \frac{\gamma_{x_2}^{RD_n}}{\gamma_{th,n}} \right) < 1 \right). \quad (24)$$

The approximate closed-form expression of the OP for the near user will be provided in the following theorem.

Theorem 2. *The approximate closed-form expression for the OP of D_n can be expressed as (25), shown at the top of the next page.*

$$\text{where } \phi_1 = \frac{\sigma_{eRD_n}^2 \gamma_1 \gamma_{th,f} + \gamma_{th,f}}{b_1 \gamma_1 - b_2 \gamma_1 \gamma_{th,f}}, \phi_2 = \frac{\sigma_{eRD_n}^2 \gamma_1 \gamma_{th,n} + \gamma_{th,n}}{b_2 \gamma_1} \text{ and } \phi = \max(\phi_1, \phi_2).$$

Proof. See Appendix B. \square

B. ASYMPTOTIC OUTAGE PROBABILITY

To gain more insights, we focus on the asymptotic analysis for the OP in the high SNR region. As in [30], at the high SNRs, Marcum Q- function can be approximated as

$$Q \left(\sqrt{2K}, \sqrt{\frac{2(K+1)x}{\lambda_i}} \right) \approx 1 - e^{-K \frac{(K+1)x}{\lambda_i}}, \quad (26)$$

and the CDF of (17) can be further approximated by

$$F_{\rho_i}^\infty(x) \approx e^{-K \frac{(1+K)x}{\lambda_i}}. \quad (27)$$

Next, the asymptotic analysis will be provided in the following corollaries.

$$P_{out}^{D_f} = 1 - \sum_{l_1=0}^{\infty} \sum_{m_1=0}^{l_1} \sum_{l_2=0}^{\infty} \sum_{m_2=0}^{l_2} \sum_{t=0}^{m_2} \binom{m_2}{t} \frac{K^{l_1+l_2}}{l_1!l_2!m_1!m_2!} \left(\frac{K+1}{\lambda_{SR}}\right)^{m_1} \left(\frac{K+1}{\lambda_{RD_f}}\right)^{m_2} \frac{2\zeta^{m_1}\psi^{m_2}}{R_f^2 - R_n^2} \times e^{-\frac{K+1}{\lambda_{SR}}\zeta - \frac{K+1}{\lambda_{RD_f}}\psi - 2K} \left(\gamma\left(\frac{\nu t+2}{\nu}, \frac{(K+1)\psi}{\lambda_i} R_f^\nu\right) - \gamma\left(\frac{\nu t+2}{\nu}, \frac{(K+1)\psi}{\lambda_i} R_n^\nu\right)\right) \nu^{-1} \left(\frac{(K+1)\psi}{\lambda_{RD_f}}\right)^{-\frac{\nu t+2}{\nu}} \quad (23)$$

$$P_{out}^{D_n} = 1 - \sum_{l_1=0}^{\infty} \sum_{m_1=0}^{l_1} \sum_{l_3=0}^{\infty} \sum_{m_3=0}^{l_3} \sum_{t=0}^{m_3} \binom{m_3}{t} \frac{K^{l_1+l_3}}{l_1!l_3!m_1!m_3!} \left(\frac{K+1}{\lambda_{SR}}\right)^{m_1} \left(\frac{K+1}{\lambda_{RD_n}}\right)^{m_3} \times \frac{2\zeta^{m_1}\phi^{m_3}}{R_n^2} e^{-\frac{K+1}{\lambda_{SR}}\zeta - \frac{(K+1)\phi}{\lambda_{RD_n}} - 2K} \nu^{-1} \left(\frac{(K+1)\phi}{\lambda_{RD_n}}\right)^{-\frac{\nu t+2}{\nu}} \gamma\left(\frac{\nu t+2}{\nu}, \frac{(K+1)\phi}{\lambda_{RD_n}} R_n^\nu\right) \quad (25)$$

Corollary 1. At high SNRs, the asymptotic closed-form of OP for D_f is given as

$$P_{D_f}^\infty = 1 - \left(1 - e^{-K\frac{(1+K)\zeta}{\lambda_1}}\right) \times \left(1 - \frac{(1+K)\psi e^{-K}}{\lambda_3} \left(1 + \frac{2(R_f^{\nu+2} - R_n^{\nu+2})}{(\nu+2)(R_f^2 - R_n^2)}\right)\right). \quad (28)$$

Proof. See Appendix C. \square

Corollary 2. At high SNRs, the asymptotic closed-form of the OP for D_n is given as

$$P_{D_n}^\infty = 1 - \left(1 - e^{-K\frac{(1+K)\zeta}{\lambda_1}}\right) \times \left(1 - \frac{(1+K)\phi e^{-K}}{\lambda_2} \left(1 + \frac{2R_n^\nu}{\nu+2}\right)\right). \quad (29)$$

Proof. See Appendix D. \square

C. DIVERSITY ORDER

Based on the derived asymptotic results, we will focus on the diversity order in the high SNR regime, which is defined as in [31]

$$d = - \lim_{\gamma' \rightarrow \infty} \frac{\log(P_{out}^\infty)}{\log \gamma'}, \quad (30)$$

where $\gamma' \in \{\gamma_1, \gamma_2\}$ is transmitted SNR and P_{out}^∞ is the asymptotic OP.

Corollary 3. The diversity order of D_f is given as

$$d_f = - \lim_{\gamma_1 \rightarrow \infty} \frac{\log(P_{D_f}^\infty)}{\log \gamma_1} = 0. \quad (31)$$

Corollary 4. The diversity order of D_n is given as

$$d_n = - \lim_{\gamma_2 \rightarrow \infty} \frac{\log(P_{D_n}^\infty)}{\log \gamma_2} = 0. \quad (32)$$

Remark 1. From Corollary 3 and Corollary 4, we can observe that the diversity orders of the far and near users in the high SNR regime are zero. This happens because the asymptotic OP is fixed as a non-zero constant due to channel estimation error. This means that the average power is not always beneficial to the system outage performance under the condition of imperfect CSI.

D. SYSTEM THROUGHPUT

In wireless communication networks, system throughput is another significant metric to evaluate the system performance. It is defined as the product of the reliable communication and the data rate. Moreover, there are two transmission modes of operation in wireless communication systems: (1) delay-tolerant transmission mode; (2) delay-limited transmission mode. In the delay-tolerant transmission mode, the systems operate under the condition of error free, and the system throughput is determined by the ergodic rate. In the delay-limited transmission mode, the systems operate under a fixed rate, and the system throughput is determined by the wireless fading channels. In this paper, the delay-limited transmission mode is considered, and the system throughput is given as⁴

$$R = \sum_{i=1}^M (1 - p_{D_m}) \times R_{th,m}, \quad (33)$$

where $R_{th,m}$ denotes the transmission data rate of D_m and can be expressed as $R_{th,m} = \frac{1}{2} \log_2(1 + \gamma_{th,m})$, the constant $1/2$ represents that the communication process is divided into two time slots and $\gamma_{th,m}$ indicates the outage threshold of user D_m .

IV. LOCATION OPTIMIZATION

As shown in (10), for the fixed transmission power, the OPs for the paired users D_n and D_f highly rely on the distance between the UAV and the user.⁵ Considering this fact, we design an optimal deployment scheme to maximize the sum rate of the proposed system under the condition of desired quality-of-service (QoS). This can be achieved by minimizing the average path-loss by shortening the average distances between the UAV and all NOMA users.⁶ In this

⁴Although we focus on the system throughput of delay-limited transmission mode, our results can be easily extended to the delay-tolerant transmission mode.

⁵In fact, the path-loss is a determined factor since that multiple path fading and shadowing fading revolves around the path-loss [32].

⁶Note that the change of position of the UAV for the satellite is negligible due to long distance between the satellite and the UAV. Therefore, for the location optimization, we only focus on the link between the UAV and users.

TABLE 1: Table of parameters for numerical results

Monte Carlo simulations	10^7 iterations
The power allocation coefficients of P_S	$a_1 = 0.7, a_2 = 0.3$
The power allocation coefficients of P_R	$b_1 = 0.8, b_2 = 0.2$
The mean square error of channel estimation error	$\sigma_{e_{SR}} = \sigma_{e_{RD_f}} = \sigma_{e_{RD_n}} = 0.07$
The variance of the additive white Gaussian noise (AWGN)	$N_0 = N_f = N_n = 1$
The Rician channel parameter	$K = 1$
The radius of inner circle and outer circle	$R_n = 0.2m, R_f = 0.8m$
The height of UAV	$h = 100m$
The path loss exponent	$\nu = 3$
The outage threshold	$\gamma_{th_f} = 0.01, \gamma_{th_n} = 1$

regard, we formulate the constrained optimization problem for location optimization as follows

$$\begin{aligned}
(P_1) \quad & \max_{X_U, Y_U} \sum_{k=1}^M \log_2(1 + \gamma_k), \\
& C_1: \log_2(1 + \gamma_{th,n}) > \zeta_n, \\
& C_2: \log_2(1 + \gamma_{th,f}) > \zeta_f, \\
& C_3: \sum_{k=1}^M a_k = 1, \\
& C_4: \min\{x_k\} \leq X_U \leq \max\{x_k\}, 1 \leq k \leq M, \\
& C_5: \min\{y_k\} \leq Y_U \leq \max\{y_k\}, 1 \leq k \leq M, \quad (34)
\end{aligned}$$

where $\zeta_n = \log_2(1 + \gamma_{th,n})$ and $\zeta_f = \log_2(1 + \gamma_{th,f})$ are the minimum rate of the paired users D_n and D_f , respectively; (x_k, y_k) is the coordinate of k -th user; and M is the total number of users. To ensure the coverage of UAV, we assume that the UAV stays at a fixed height, and the coordinate of the UAV is (X_U, Y_U, h) . To solve the problem (P_1) , we first have the following proposition.

Proposition 2. *Under the conditions of a fixed transmit average power, the problem (P_1) is an increasing function with respect to ρ_{RD_i} for $\rho_{RD_i} \geq 0$.*

Proof. The proof can be divided into two cases:

1) When (7) or (9) is considered, the rate can be represented as a unified form as

$$f(x) = \log_2 \left(1 + \frac{\Theta_1 x}{\Theta_2 x + \Theta_3} \right), \quad (35)$$

where $x \in \{\rho_{RD_f}, \rho_{RD_n}\}$, $\Theta_1 = b_1 \gamma_1$, $\Theta_2 = b_2 \gamma_2$ and $\Theta_3 \in \{\sigma_{e_{RD_f}}^2 \gamma_1 + 1, \sigma_{e_{RD_n}}^2 \gamma_1 + 1\}$.

2) When (8) is considered, the rate can be represented as a unified form as

$$f(x) = \log_2(1 + \Delta x), \quad (36)$$

where $\Delta = b_2 \gamma_1 / (\sigma_{e_{RD_n}}^2 \gamma_1 + 1)$.

For the first case, we can find that the function $f(x)$ is an increasing function with respect to x since the first-order derivative function of $f(x)$ is positive, which is presented as follows

$$f'(x) = \frac{\Theta_1 \Theta_3}{((\Theta_1 + \Theta_2)x + \Theta_3)(\Theta_2 x + \Theta_3)} > 0. \quad (37)$$

For the second case, we have the same result by similar methodology.

Therefore, we have the conclusion of Proposition 2. \square

Based on (10), the problem is equivalent to the following one:

$$\begin{aligned}
(P_2) \quad & \min_{X_U, Y_U} \sum_{k=1}^M d_k, \\
& s.t. \quad C1: \min\{x_k\} \leq X_U \leq \max\{x_k\}, 1 \leq k \leq M, \\
& \quad C2: \min\{y_k\} \leq Y_U \leq \max\{y_k\}, 1 \leq k \leq M, \quad (38)
\end{aligned}$$

where d_k is the distance between the k -th user and the UAV. The distance d_k can be expressed as

$$d_k = \sqrt{h^2 + (X_U - x_k)^2 + (Y_U - y_k)^2}. \quad (39)$$

To obtain the optimal location of the proposed framework, the derived result is provided in the following theorem.

Theorem 3. *The optimal coordinates X_U^* and Y_U^* of the UAV are given as*

$$\begin{aligned}
X_U^* &= \sum_{k=1}^M \frac{x_k}{M}, \\
Y_U^* &= \sum_{k=1}^M \frac{y_k}{M}. \quad (40)
\end{aligned}$$

Proof. See Appendix E. \square

Remark 2. *From Theorem 3, we can conclude that the sum rate can be maximized by carefully designing optimal location of the UAV, and the optimal x -coordinate and y -coordinate of the UAV are the mean of the x -coordinate and y -coordinate of all the users, respectively.*

V. NUMERICAL RESULTS

In this section, we evaluate the OP, throughput and optimal UAV location performances via numerical results. The complementary performance evaluation results obtained by means of Monte-Carlo computer simulation trials is presented to verify the accuracy of the theoretical analysis in Sections III and IV. Unless otherwise stated, we use the parameter settings shown in Table 1.

Fig. 2 depicts results of the OP versus the average SNR of the far and near users. For the sake of comparison, the curves for the OP under ideal conditions ($\sigma_{e_{SR}} = \sigma_{e_{RD_n}} = \sigma_{e_{RD_f}} = 0$) is provided. From Fig. 2, one can observe

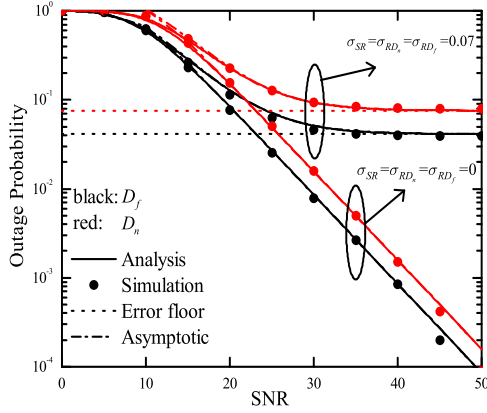


FIGURE 2: OP of the far and near users for different channel estimation errors vs. transmit SNR

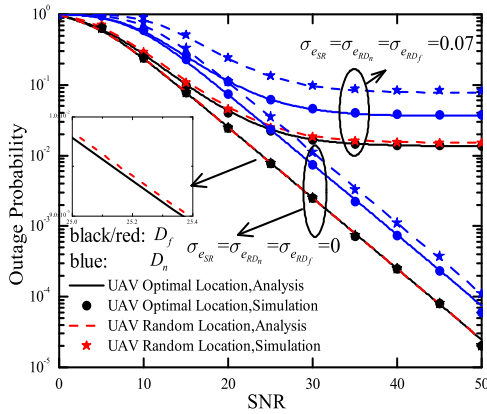


FIGURE 3: OP of UAV for different channel estimation errors in optimal location vs. random location

that the theoretical analytical results of (23), (25) and (28), (29) match with the simulated results, which verified the correctness of our analysis. Moreover, one can also observe that the curves of the analytical OP almost overlap with the asymptotic result in terms of outage probability in the moderate and high SNR region. This figure also indicates that there are error floors for the OP at high SNRs because of the channel estimate error, which verifies the conclusion in Remark 1. This means that we cannot improve the outage probability by increasing the average SNR. However, under ideal conditions, the average SNR is always beneficial to the OP.

Fig. 3 plots the OP of the far and the near users versus the average SNR for different channel estimation errors σ_{e_i} . In this simulation, we consider two scenarios for the UAV: 1) optimal location; 2) random location. As one can see, the curves of theoretical analysis sufficiently coincide with the Monte Carlo curves for the two scenarios. Furthermore, the outage performance of the first scenario outperforms that of the second scenario, which implies that the proposed location optimization scheme can minimize the OP. Finally,

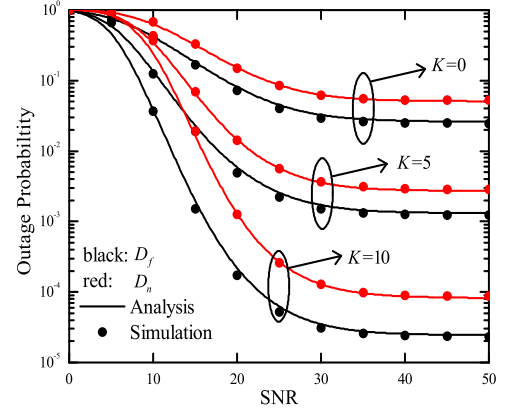


FIGURE 4: OP in different Rician factors

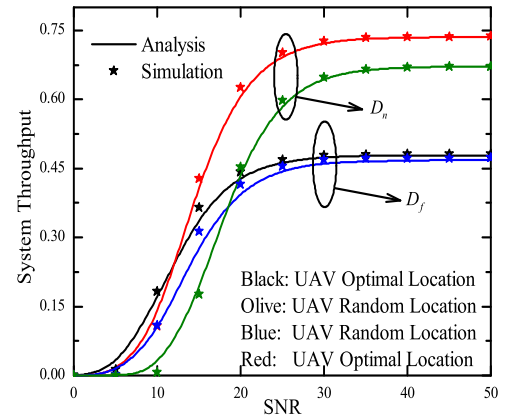


FIGURE 5: System Throughput of UAV in optimal location vs. random location

we can also observe that the near user is more sensitive to the location of UAV than that of the far user.

In Fig. 4, we show the OP versus the average SNR for different Rician factors $K = \{0, 5, 10\}$. When Rician factor is 0 ($K=0$), the Rician fading reduces to the Rayleigh fading. It can be seen that for an increase in the values of K , the OP declines, whereas for small values of K ($K=0$) the OP increases. This means that for large K ($K=10$), there is a strong LoS condition to support the communication, which yields good outage performance. It can also be seen that there are error floors for the outage probability for all Rician factor settings due to channel estimation error. It indicates that UAV communication can provide reliability communication. Finally, we note that the derived approximate expressions remain sufficient tight for the whole SNR range.

In Fig. 5, we have compared the proposed optimization scheme with the random UAV deployment scheme. From Fig. 5, we note that the system throughput with optimal location scheme outperforms the random UAV scheme since the optimization scheme has the smallest path-loss caused by the shortest average distance between the UAV and users. Similar results can be seen that there exist ceilings for the

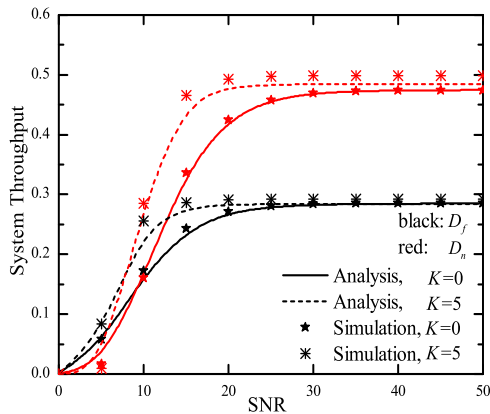


FIGURE 6: Throughput in different Rician factors

system throughput at high SNRs due to the fixed constant for the OP caused by channel estimation error. We have observed that the OP of the near user is superior to the far user from Fig. 2. According to the relationship between throughput and OP, which is that the larger the OP, the smaller the throughput, the system throughput of the near user should be superior to the far user. The curves of system throughput for the near user is above that for the far user in Fig. 5. This result verifies the validity of the theoretical analysis.

Fig. 6 shows system throughput versus transmit SNR for different Rician factors $K = \{0, 5\}$. As stated before, when Rician factor is 0, the fading channel reduces to the Rayleigh fading channel. We note that the throughput tends to a fixed constant as the average SNR grows large. This happens because at high SNRs, there exists an error floor caused by channel estimation error. These results are consistent with Fig. 5. Also, it can be seen that Rician factor has more severe effects on the near user than the far user because of strong LoS. As in Fig. 4, a large value of Rician factor yields a high throughput.

VI. CONCLUSION

In this paper, the performance of HS-UAV NOMA network over Rician fading channels is studied. Specifically, we derived the analytical approximate expressions for the outage probability and system throughput for the far and near users in the presence of channel estimation error. Based on the derived approximations, we explore the asymptotic behavior in the high SNR regime, as well as the diversity orders. We demonstrate that there are floors for the outage probability caused by non-ideal channel estimation. To further improve system performance, we design an optimal location scheme for the UAV. As illustrated by simulation results, the proposed scheme outperforms the random UAV scheme, specifically for the far users.

APPENDIX A: PROOF OF THEOREM 1

The proof starts by simplifying (22) to the following form as

$$\begin{aligned} P_{out}^{D_f} &= 1 - \Pr(\gamma_{x_1}^{SR} \geq \gamma_{th,f}, \gamma_{x_2}^{SR} \geq \gamma_{th,n}, \gamma_{x_1}^{RD_f} \geq \gamma_{th,f}) \\ &= 1 - \Pr(\rho_{SR} \geq \zeta) \Pr(\rho_{RD_f} \geq \psi) \\ &= 1 - (1 - F_{\rho_{SR}}(\zeta)) (1 - F_{\rho_{RD_f}}(\psi)). \end{aligned} \quad (A.1)$$

Substituting (17) and (19) into (A.1), we can get (A.2), shown at the top of the next page.

After some algebra operations, we can conclude the proof of the Theorem 1.

APPENDIX B: PROOF OF THEOREM 2

Based on (24), the near user D_n can be simplified to (B.1), shown at the top of the next page.

Substituting (17) and (18) into (B.1), we can get (B.2), shown at the top of the next page.

After some algebra operations, we can conclude the proof of Theorem 2.

APPENDIX C: PROOF OF COROLLARY 1

Combined (13) with (27), the CDF of $|h_f|^2$ is approximated by

$$F_{|h_f|^2}(x) \approx \frac{(1+K)xe^{-K}}{\lambda_i} \left(1 + \frac{2(R_f^{\nu+2} - R_n^{\nu+2})}{(\nu+2)(R_f^2 - R_n^2)} \right). \quad (C.1)$$

Substituting (27) and (C.1) into (A.1), we can obtain

$$\begin{aligned} P_{D_f}^\infty &= 1 - \left(1 - e^{-K \frac{(1+K)\zeta}{\lambda_1}} \right) \\ &\times \left(1 - \frac{(1+K)\psi e^{-K}}{\lambda_3} \left(1 + \frac{2(R_f^{\nu+2} - R_n^{\nu+2})}{(\nu+2)(R_f^2 - R_n^2)} \right) \right). \end{aligned} \quad (C.2)$$

APPENDIX D: PROOF OF COROLLARY 2

Combined (12) with (27), the CDF of the squared channel gain $|h_n|^2$ is approximated by

$$F_{|h_n|^2}(x) \approx \frac{(1+K)xe^{-K}}{\lambda_i} \left(1 + \frac{2R_n^\nu}{\nu+2} \right). \quad (D.1)$$

Substituting (27) and (D.1) into (B.1), we can obtain (D.2).

$$\begin{aligned} P_{D_n}^\infty &= 1 - \left(1 - e^{-K \frac{(1+K)\zeta}{\lambda_1}} \right) \\ &\times \left(1 - \frac{(1+K)\phi e^{-K}}{\lambda_2} \left(1 + \frac{2R_n^\nu}{\nu+2} \right) \right). \end{aligned} \quad (D.2)$$

APPENDIX E: PROOF OF THEOREM 3

For the problem (P_2) , based on (39), the problem (P_2) is equivalent to

$$\begin{aligned} (P_3) \quad &\min_{X_U, Y_U} \sum_{k=1}^M (X_U - x_k)^2 + (Y_U - y_k)^2 \\ &s.t. \min \{x_i\} \leq X_U \leq \max \{x_i\}, 1 \leq i \leq M \\ &\min \{y_j\} \leq Y_U \leq \max \{y_j\}, 1 \leq j \leq M. \end{aligned} \quad (E.1)$$

We note that (P_3) is a convex function with respect to X_U and Y_U since the second derivative of X_U or Y_U is $2M > 0$. Moreover, the constraint conditions of (P_3) are

$$P_{out}^{D_f} = 1 - e^{-K} \sum_{l_1=0}^{\infty} \sum_{m_1=0}^{l_1} \frac{K^{l_1}}{l_1! m_1!} \left(\frac{K+1}{\lambda_{SR}} \right)^{m_1} \zeta^{m_1} e^{-\frac{K+1}{\lambda_{SR}} \zeta} \frac{2}{R_f^2 - R_n^2} e^{-K} \sum_{l_2=0}^{\infty} \sum_{m_2=0}^{l_2} \frac{K^{l_2}}{l_2! m_2!} \left(\frac{K+1}{\lambda_{RD_f}} \right)^{m_2} \psi^{m_2} e^{-\frac{K+1}{\lambda_{RD_f}} \psi} \\ \times \sum_{t=0}^{m_2} \binom{m_2}{t} \left(\gamma \left(\frac{\nu t + 2}{\nu}, \frac{(K+1)\psi}{\lambda_i} R_f^\nu \right) - \gamma \left(\frac{\nu t + 2}{\nu}, \frac{(K+1)\psi}{\lambda_i} R_n^\nu \right) \right) \nu^{-1} \left(\frac{(K+1)\psi}{\lambda_{RD_f}} \right)^{-\frac{\nu t + 2}{\nu}} \quad (\text{A.2})$$

$$P_{out}^{D_n} = 1 - \Pr(\gamma_{x_1}^{SR} \geq \gamma_{th,f}, \gamma_{x_2}^{SR} \geq \gamma_{th,n}) \Pr(\gamma_{x_1}^{RD_n} \geq \gamma_{th,f}, \gamma_{x_2}^{RD_n} \geq \gamma_{th,n}) \\ = 1 - \Pr(\rho_{SR} \geq \zeta) \Pr(\rho_{RD_n} \geq \phi) \\ = 1 - (1 - F_{\rho_{SR}}(\zeta)) (1 - F_{\rho_{RD_n}}(\phi)) \quad (\text{B.1})$$

$$P_{out}^{D_n} = 1 - \sum_{l_1=0}^{\infty} \sum_{m_1=0}^{l_1} \sum_{l_3=0}^{\infty} \sum_{m_3=0}^{l_3} \sum_{t=0}^{m_3} \binom{m_3}{t} \frac{K^{l_1+l_3}}{l_1! l_3! m_1! m_3!} \left(\frac{K+1}{\lambda_{SR}} \right)^{m_1} \left(\frac{K+1}{\lambda_{RD_n}} \right)^{m_3} \\ \times \frac{2\zeta^{m_1} \phi^{m_3}}{R_n^2} e^{-\frac{K+1}{\lambda_{SR}} \zeta - \frac{(K+1)\phi}{\lambda_{RD_n}} - 2K} \nu^{-1} \left(\frac{(K+1)\phi}{\lambda_{RD_n}} \right)^{-\frac{\nu t + 2}{\nu}} \gamma \left(\frac{\nu t + 2}{\nu}, \frac{(K+1)\phi}{\lambda_{RD_n}} R_n^\nu \right) \quad (\text{B.2})$$

linear functions, and thus, it is a convex problem. Therefore, above problem can be solved by a convex method. The first-order derivative of (E.1) with X_U and Y_U can be computed as $2MX_U - 2\sum_{k=1}^M x_k$ and $2MY_U - 2\sum_{k=1}^M y_k$, respectively. When the first-order derivative equal to 0, the optimal solution can be obtain. Therefore, the optimal solutions of X_U and Y_U can be denoted as

$$X_U^* = \sum_{k=1}^M x_k / M, \quad (\text{E.2})$$

and

$$Y_U^* = \sum_{k=1}^M y_k / M. \quad (\text{E.3})$$

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